ULTRASONIC C-SCAN STANDARDIZATION FOR POLYMER-MATRIX COMPOSITES - ACOUSTIC CONSIDERATIONS

R.A. Smith, D.A. Bruce, L.D. Jones, A.B. Marriott, L.P. Scudder, and S.J. Willsher

Structural Materials Center
Defence Evaluation and Research Agency
Farnborough
Hampshire GU14 0LX, UK

INTRODUCTION

Ultrasonic C-scan inspection techniques are widely used for the non-destructive evaluation of fiber-reinforced polymer composites. A C-scan is any two-dimensional scan of a specimen that produces a map of a parameter, such as reflected amplitude, as it varies across the surface of the specimen. The technique can be used to detect, measure and characterize a wide range of manufacturing and in-service defects in these materials. At present there is no international or national standard operational procedure available for ultrasonic C-scan inspection of fiber-reinforced composite structures - current standards are directed towards the inspection of metals.

A number of companies within the Aerospace/Defense industry are currently using either the McDonnell Douglas Process Standard DPS 4.738-2 or, to a lesser extent, Boeing Aircraft Company Process Specification Number BAC5980.

This paper summarizes the acoustical considerations in a program to develop a new international standard, funded by the Department of Trade and Industry, involving the Structural Materials Center, Defence Evaluation and Research Agency (DERA), Farnborough and the National Physical Laboratory (NPL), Teddington. The new standard will be based on procedures collected from both UK and international industrial users. Although current use of the new standard is primarily targeted at aerospace-type materials, a wider use is foreseen.

One of the aims of the program when it was initiated was to investigate the poor reproducibility and overcome the many short-comings of current C-scanning practice. This initially required a thorough understanding of the ultrasonic propagation in, and interaction with, the composite material. Then the limitations of using the less-than-ideal conventional equipment for flaw detection needed to be determined. Finally new procedures to overcome these limitations, where possible, would be required for drafting into the new standard.

SCOPE

The three basic ultrasonic inspection methods covered in this program are summarized below.

Pulse-echo method

The pulse-echo method, using a single transducer operating as a transmitter-receiver which is scanned in a plane parallel to the specimen, is applicable where inspection access is limited to one side of a structure. It can be used for measuring double-pass absolute attenuation by comparing front- and back-surface reflections. A short pulse length is required to prevent reflections from near-surface defects interfering with the reflections from the adjacent surfaces.

Single through-transmission method

This method involves two separate ultrasonic transducers (ie transmitter and receiver) facing directly opposite each other and separated by the specimen. Defects in the specimen will either block or attenuate the transmitted ultrasonic signal. Water-jet (squirter) systems can be employed to provide ultrasonic coupling, each system containing a pair of jets. Roller contact transducers, preferably lubricated with a thin film of water, can also be used and are well suited to the inspection of structures with simple curvatures.

Double through-transmission method

In this inspection method, a reflector plate is positioned behind the specimen with a water gap between the two. The specimen, transducer and reflector plate are fully immersed in water. A single transducer operating as a transmitter-receiver is scanned in a plane parallel to the specimen surface and only the reflection from the reflector plate is monitored. The double through-transmission approach does not have the same problem as the pulse-echo method for the detection of near-surface defects. Discontinuities will partially reflect the incident beam thus reducing the energy of the transmitted pulse that propagates to the reflector and back.

IMPORTANT ACOUSTICAL EFFECTS

Reflection and transmission at an interface

Sound-waves propagate through a material and are modified during their propagation by the boundaries encountered, by the material itself and by the presence of defects. In general, all of these interactions are complicated; the exact nature of the interaction depending on parameters such as the relative size of the feature to the wavelength of sound, the orientation of the feature and the mode in which the sound-wave is propagating.

For the special case of normal incidence at the interface between two different materials, the relative amplitudes and phases of the reflected and transmitted waves depend upon the change in acoustic impedance across the boundary.

When the sound-wave is incident at some angle the amplitudes of the reflected and transmitted waves again depend upon the change in acoustic impedance but also upon the angle of incidence. The directions of propagation of these waves obey Snell's Law, as in optics. The interaction is complicated in solids since, in general, wave mode types other than the incident wave type will be generated; thus an incident compression wave may produce a reflected and transmitted compression wave plus a shear wave and, if the wave is incident at a particular angle, surface wave components may be generated. It can be seen that even a simple interaction can generate a number of sound waves in addition to that deliberately propagated. This mode conversion will result in a loss of energy from the initial ultrasonic wave and explains the existence of reflections at unexpected propagation times. Interest in non-normal incidence during this programme was confined to the use of focused transducers which generate a range of angles of incidence.

Diffraction in unfocused ultrasound beams

An unfocused (planar) transducer produces a beam with two distinct regions: the near field where the beam width remains fairly constant and the beam profile changes with distance, and the far field where the beamwidth increases with distance and the beam profile remains constant. The distance of the transition between these two regions (known as the near-field distance or last-axial maximum), Y_0^+ is given approximately by:

$$Y_0^+ \approx \frac{a^2}{\lambda} \tag{1}$$

where a is the radius of the transducer and λ is the wavelength of the ultrasound.

The ultrasonic field from a plane piston is quite complicated if it is driven continuously at a single frequency (continuous-wave). However, in pulsed mode, as used for C-scan inspections, the beam profile becomes simpler. Instead of the complex interference pattern near to the face of a continuously-driven probe, the pulsed version has a conical plane-wave region within which the so-called plane and edge waves do not interfere because they are separated in time.

The extent of this plane-wave region depends on the probe size, frequency and number of cycles in the excitation pulse. A general formula for calculating the nominal axial extent of the plane-wave region [1], N_{pw} is:

$$N_{pw} = \frac{a^2}{2n\lambda} - \frac{n\lambda}{2} \tag{2}$$

where a is the radius of the probe element, λ is the center wavelength of the pulse and n is the number of cycles in the actual ultrasonic pulse. This formula assumes the end of the plane-wave region is the on-axis distance where the plane-wave and edge-wave just begin to interfere.

Operating in the near-field of a transducer, it is possible to reduce the beamwidth and improve the spatial resolution by using a collimator. This is a baffle of absorbent material with a circular hole on the axis. The hole then defines the effective size of the transducer so the last-axial maximum will move closer to the transducer. The advantage of using a collimator or a focused transducer is that the good penetration of a low frequency can be combined with the improved spatial resolution of a small transducer.

Diffraction in focused ultrasound beams

The diffraction effects in a focused field are similar to the unfocused case in that a short pulse excitation will produce a region near to the transducer with no interference effects. The difference is that the wavefronts are not planar but spherical (assuming the focusing is spherical) in this region and they converge on the focal point. The maximum amplitude will be in the focal region on axis.

The beamwidth is considerably smaller in the focal region than for an unfocused transducer at the last axial maximum. The f-number (ie focal length / aperture diameter) is used to describe the tightness of the focusing as in geometrical optics. The smaller the f-number the smaller the beamwidth at the focus, but ultimately the minimum beamwidth is governed by the ratio of the transducer diameter to the wavelength of the ultrasound [2].

Diffraction at an edge

Diffraction at an edge is similar to that in optics if mode conversion effects are ignored. Thus, for a straight-edged delamination insonated by plane waves a Fresnel diffraction curve is appropriate [3]. The effect is to cause errors in positioning that edge, and these were dealt with in the -6dB defect sizing sections of this program.

Insertion of a solid plate in an ultrasound beam

Ultrasonic fields from finite-sized transducers are subject to diffraction effects which cause the spatially-averaged received signal to vary greatly depending on the position in the field of the receiver. This is true for both single- and dual-transducer modes of operation. For most non-destructive testing methods the first-order diffraction effects are reduced by ensuring that the receiver is perpendicular to, and centered on, the beam axis. This leaves only the axial variations due to diffraction. In general these are ignored for C-scans and insertion loss measurements rarely correct for the changes in the diffractive field when a specimen is inserted.

The effects of this omission can be illustrated by considering a focused transducer, used in the double through-transmission method, which is focused on a reflector plate with no specimen present. As soon as the specimen is placed in the ultrasound beam two things happen: firstly the attenuation of water (proportional to frequency-squared over the range 3-70 MHz[4]) is replaced by the attenuation of the specimen (usually greater and proportional to the frequency) over the specimen thickness; secondly the higher acoustic velocity in the specimen than in the water causes the focal point to move nearer to the transducer (see next section).

Refraction in a solid

The higher acoustic velocity in the specimen causes the focal point or last axial maximum, Y_0^+ to move nearer to the transducer by a distance δ given by:

$$\delta = \left(\frac{c_{specimen}}{c_{water}} - 1\right) Thickness \tag{3}$$

where $c_{specimen}$ and c_{water} are the acoustic velocities in the specimen and water respectively. Thus a specimen made from a material with twice the acoustic velocity of water (eg carbon-fiber polymer-matrix composite) will move the focus closer to the transducer by an amount approximately equal to the specimen thickness.

The effect of shifting the focal point or Y_0^+ can be dealt with quite easily by introducing an axial translation of the transducer to compensate for the shortening of the focal length. Thus, in the case mentioned in the preceding paragraph, moving the transducer nearer to the specimen by an amount equal to the specimen thickness. However, the total water path has now decreased by twice the specimen thickness per pass through the specimen (ie four times for double through-transmission or pulse-echo). This reduces the attenuation due to the water and a further correction is required.

Attenuation in water in low-amplitude fields

For sinusoidal waves in water, the linear-regime attenuation coefficient applies. At 20^{o}C the value is 2.1715×10^{-4} dB mm^{-1} MHz^{-2} [3]. This attenuation figure is only valid in the linear regime - ie for low-pressure ultrasonic signals - and its frequency-dependence makes it hard to apply to pulsed ultrasonic signals. To a first approximation the peak-frequency can be used to determine the attenuation. For higher amplitude signals it is necessary to consider the effects of nonlinear propagation in water (see below).

Nonlinear attenuation in water in finite-amplitude fields

In higher-amplitude fields the oscillations are no longer sinusoidal because the periodic density variations in the beam cause periodic changes in the sound velocity. Thus the compression wavefronts catch up with the rarefaction wavefronts and eventually produce a sawtooth-shaped (or 'shocked') waveform [5]. The distortion in the waveform (see Figure 1) means that there are higher harmonics present and that energy has been transferred from the fundamental frequency band into these higher bands. This distortion is not observed by standard flaw-detection systems because of their limited bandwidth.

The characteristic sawtooth waveform caused by nonlinear propagation is generated over a finite distance. Hence, the waveform at short distances will not appear shocked but after propagating through the water the waveform will appear distorted. Thus the effect is dependent on both signal amplitude and propagation distance.

The harmonic frequencies that are generated due to this nonlinear propagation phenomenon in water are subject to a much larger attenuation. This means that energy transferred out of the fundamental band is attenuated more rapidly. As the narrow-band flaw detection systems are insensitive to the harmonic frequencies, the measured attenuation in water is considerably enhanced by nonlinear propagation.

Studies of the effect on pulsed waveforms from focused and unfocused transducers have suggested that the loss in amplitude of the fundamental can considerably enhance the attenuation in water [5]. At high levels of waveform distortion an attenuation of more than ten times the linear attenuation coefficient has been measured.

The effect is also dependent on the fundamental frequency - the higher the frequency the shorter the distance and lower the amplitude has to be before nonlinear propagation

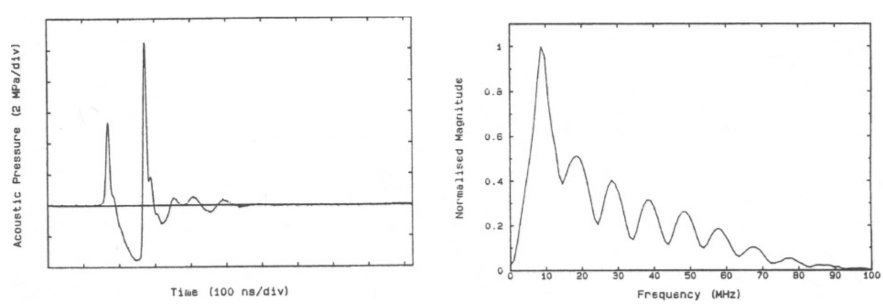

Figure 1. Acoustic waveform and its FFT from a conventional commercially-available 10 MHz focused transducer measured at the focus, 34 mm, using a broad-band PVDF membrane hydrophone [6]. Measurements were made at the National Physical Laboratory.

becomes important. However, the situation is a little more complicated than this as at much higher frequencies in water (above those commonly used for non-destructive testing), where the low-amplitude attenuation (approximately proportional to frequency-squared) becomes dominant, the fundamental does not suffer from such an enhancement of attenuation.

Correcting for this phenomenon is beyond current capabilities for pulsed flaw detection systems. However, it is possible to recommend conditions under which the effects can be minimized where relative or absolute attenuation measurements are important. These conditions are: a) low frequency: use of a lower frequency for the specimen inspection, b) low amplitude: use of the lowest amplitude setting which gives a reasonable signal-to-noise, and c) short distances: minimize the propagation distances in water.

Attenuation in solids

The mechanisms of attenuation in solids are absorption, scattering and mode conversion. The latter occurs only at discontinuities where there is a chance for cross-coupling between modes such as longitudinal and transverse propagation modes. Absorption is caused by the conversion of the ultrasound energy to heat via several mechanisms of which the primary one is the visco-elastic damping. Rapid oscillations lose more energy than slow ones. Thus we find that attenuation due to absorption is linearly dependent on frequency.

Scattering results from inhomogeneities in the material. Discontinuities in the acoustic impedance will scatter the ultrasound and as the size of the scatterer reduces to less than the wavelength, the wavefront will be scattered more than geometrically divided. Hence the scattering will be very frequency dependent, more so than the absorption contribution to the attenuation.

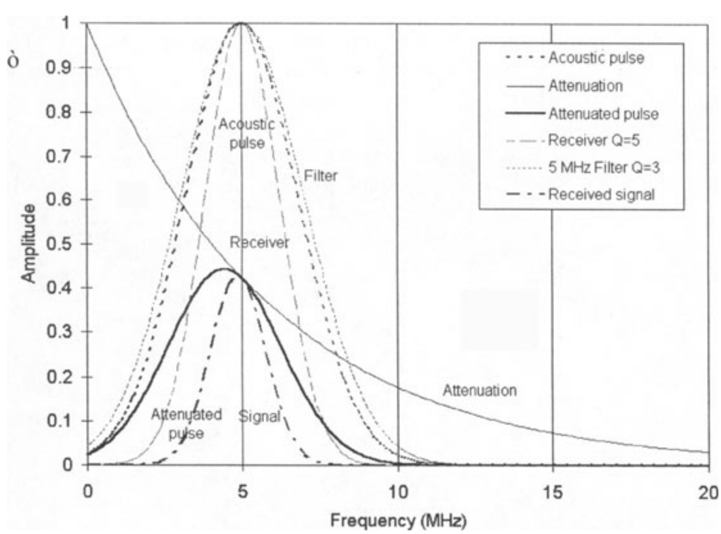

Figure 2. Illustration of the peak-frequency downshift caused by linearly frequency-dependent attenuation (as for most solids). The effect is reduced by using a narrow-band receiver and filter. Hence the received signal has a peak frequency nearer to the original 5 MHz than the attenuated pulse.

Peak-frequency downshift due to attenuation

Attenuation in water is approximately proportional to the square of the frequency but the attenuation is relatively low at normal C-scanning frequencies. In solids, however, the relationship is approximately linear with attenuations being much higher than in water.

Thus propagation through water or, to a much greater extent due to higher attenuations, through a specimen, causes a down-shift in the peak frequency of a pulsed waveform (see illustration in Figure 2). The simple measurement of the peak amplitude in the pulse is sensitive to the amplitudes of frequency components around the peak frequency. This down-shift will thus lower the measured bulk attenuation coefficient for broad-band receiver systems.

Although a correction method may be possible, it would be preferable to find a measurement regime in which the problem is minimized. Figure 2 illustrates how the use of a narrow-band receiver and filter can minimize this effect. Alternatively a Fast Fourier Transform (FFT) of the received signal would remove the effect totally but this feature is generally unavailable.

SUMMARY OF RESULTS

Absolute and bulk attenuation measurements

Systematic uncertainties in attenuation measurements were found to be dependent on: diffraction in the ultrasound beam, refraction in the specimen, nonlinear propagation in the water coupling medium, and peak-frequency downshift due to the frequency-dependent attenuation. The uncertainties in measuring absolute attenuation may be reduced as follows:

a) Choose a frequency below 6 MHz to minimise the effects of nonlinear propagation in the water and downshift of the peak frequency.

b) Choose a frequency above 2 MHz to reduce diffraction effects.

c) It is extremely important to avoid the frequencies at which resonances occur between ply interfaces. For unidirectional plies spaced at 8 plies/mm this frequency is usually approximately 11.5 to 12 MHz. There may be an additional resonance for woven fabrics at approximately 6 MHz for 0.25 mm plies although resonances at other frequencies have been seen in practice. Thickness-mode resonances are also possible for thin specimens where the pulse length in the specimen is more than twice the thickness.

d) To minimise the effect of peak-frequency downshift, short water paths should be used. To isolate the frequency at which the attenuation is to be measured, use either a single frequency from a FFT of the received signal, or a narrow-band transducer and narrow-band filter in the flaw detector.

e) Work in the plane-wave region (as near to the transducer face as possible) of a large-diameter unfocused transducer to minimise diffraction effects.

f) Check that the maximum signal is being measured (ie check the alignment of the acoustic axis) before recording each measurement. This minimises the effects of non-uniform thicknesses.

g) Use low-amplitude pulser settings and short water paths to minimise the effects of nonlinear propagation in the water.

6 dB drop defect sizing

The effects of diffraction and shadowing on the 6 dB drop defect sizing method were investigated and quantified. Minimum uncertainties apply to the defect-gated pulse-echo scans and single through-transmission scans with transducers focused on the defect. If a double through-transmission or back-wall gated pulse-echo scan is required then highest accuracy results when using a focused transducer focused on the reflection that is being monitored. For double through-transmission the reflector should be placed as near as possible to the back of the specimen.

CONCLUSION

This joint program between the National Physical Laboratory and the Defence Evaluation and Research Agency was established to address the need for an international standard for ultrasonic C-scan inspection of composite materials. The first phase of the program has investigated the uncertainties in ultrasonic C-scanning of fiber-reinforced polymer composites and a draft standard has been produced for use in a round-robin exercise. This standard recommends best practice and provides the means to assess systematic uncertainties in the system being used.

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